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Towards superfast 3D optical metrology with digital micromirror device (DMD) platforms

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ABSTRACT

This paper summarizes our decade-long research efforts towards superfast 3D shape measurement leveraging the digital micromirror device (DMD) platforms. Specifically, we will present the following technologies: (1) high-resolution real-time 3D shape measurement technology that achieves 30 Hz simultaneous 3D shape acquisition, reconstruction and display with more than 300,000 points per frame; (2) Superfast 3D optical metrology technology that achieves 3D measurement at a rate of tens of kHz utilizing the binary defocusing method we invented; and (3) the improvement of the binary defocusing technology for superfast and high-accuracy 3D optical metrology using the DMD platforms. This paper will present both principles and experimental results.

Keywords: Superfast 3D optical metrology, binary defocusing, phase-shifting, fringe analysis, structured light

1. INTRODUCTION

Recent advancements in 3D computational methods have led to high-resolution real-time 3D shape measurement techniques that have been successfully applied to numerous areas including manufacturing, medical sciences, homeland security, and entertainment.

3D shape measurement technologies have seen substantial growth over the past few decades, and numerous techniques have been developed to recover 3D objects with different principles.[1,2] The most popular methods include the time of flight, laser triangulation, shape from focus and defocus, stereo vision, structured light, and digital fringe projection. Each technology was developed to solve the challenging problems of the time for some specific application. However, no existing technology can conquer all of those challenges in each domain, and thus selecting the proper 3D shape measurement technique for a particular application is still necessary. The handbook[3] assembles a number of 3D shape measurement techniques and puts them side by side, making it easier for users to determine the right method for their specific application.

The structured light method became one of the most important 3D shape measurement technologies for both scientific research and industrial practices mainly because of its simplicity and speed.[4] Real-time to high-speed 3D shape measurement has become even more popular because the processing power of a regular, modern computer (even a tablet) can handle such large amounts of data.[5] In our view, *real-time 3D shape measurement* includes three major components: acquisition, reconstruction, and redisplay all occur at speeds of 24 Hz or higher.

Even though there are real-time 3D shape measurement techniques developed based on other principles, such as time of flight,[6] active stereo vision,[7] and structured light,[8] the digital fringe projection (DFP) techniques stand out because of their overwhelmingly advantageous features (e.g., high spatial and temporal resolution) over other types of techniques.[1] The DFP technique is special kind of structured light method in that the structured patterns vary sinusoidally and continuous in both u and v directions.

This paper presents our decade-long research efforts towards superfast 3D shape measurement using the digital micromirror device (DMD) platforms. Firstly, we will present the first-ever high-resolution real-time 3D optical metrology system using the digital fringe projection (DFP) method that we developed: the system can simultaneously acquire, reconstruct, and re-display 3D shapes at 30 Hz with over 300,000 measurement points per frame.[9] We will then present our recent innovations on the digital binary phase-shifting technique[10] that has demonstrated its merits over the conventional sinusoidal phase-shifting method in terms of measurement speed and simplicity by achieving kHz rate 3D optical metrology without worrying about the nonlinearity of the projection system.[11] These speed breakthroughs were enabled by the digital-light-processing (DLP) Discovery platform and more recently the DLP LighCrafter and DLP LightCommander

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platforms. We have also found that the binary defocusing technique is not trouble free: the squared binary method has smaller measurement depth range than the conventional method. To address this challenge, we have developed methods to improve the measurement accuracy without sacrificing the measurement speed as well as methods to increase the measurement depth range without losing measurement quality. Specifically, this paper will summarize the developments of the optimal pulse width modulation (OPWM)[12] and the binary dithering/halftoning techniques[13] for high-quality superfast 3D shape measurement with the binary defocusing method. Principles of each technique will be presented, and experimental results will be shown to verify its performance.

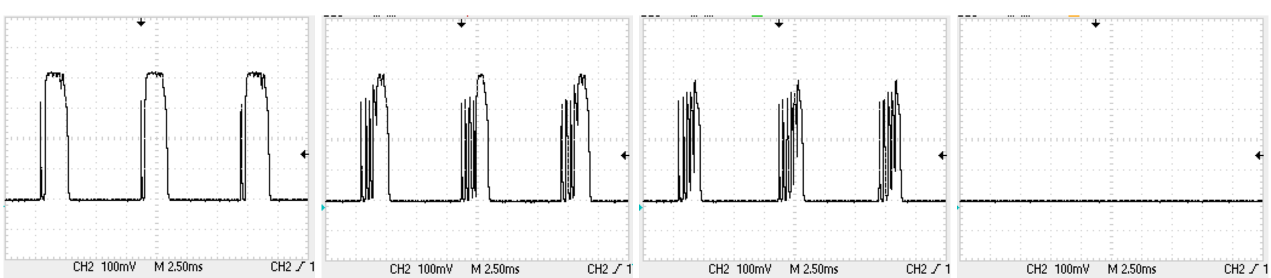
It should be emphasized that the majority of the technologies covered in this paper have already been developed and published elsewhere; this paper serves as a sort of review, from our own experience and perspective, on how the real-time 3D shape measurement technologies evolve by leveraging the unique features of hardware technologies. We hope that this paper provides the readers with a coherent piece of literature on the status of the most recent superfast 3D shape measurement technologies, motivates them to further advance these technologies, and drives them to adapt the technologies for their specific applications.

Section 2 discusses the basics of the DLP technology and the phase-shifting algorithm we used. Section 3 presents the first real-time 3D shape measurement system which was developed by modifying the commercially available DLP projectors. Section 4 presents the recent superfast 3D shape measurement development which was accomplished by inventing the binary defocusing technique and leveraging recent DLP hardware technologies. Lastly, Section 5 summarizes this paper and provides an overview on some challenges that we are still facing.

2. PRINCIPLE

2.1 Grayscale image generation mechanism of digital light processing (DLP) technology

It is well known that the DLP projector produces grayscale values by time modulation.[14] Specifically, the digital micromirror device (DMD) modulates the grayscale values by properly tilting the mirrors either into or away from the optical path at a rapid speed and with a proper timing ratio to produce the image's pixels. Figure 3(b) illustrates the waveform of the timing signal under different grayscale values. In these experiments, a photodiode sensor (Thorlabs FDS100) was used to detect the output light. The photoelectric current signal was then converted into a voltage signal and monitored by an oscilloscope. Only the green channel was used for these experiment to better visualize the effect. These experimental results demonstrated that when the projector is fed with a pure green image (RGB = (0, 255, 0)), the DMD is almost 100% ON. When the grayscale value was reduced to 128 and then 64, the irregular waveforms were generated with an approximate 50% and 25% ON time, respectively, during the projection cycle. Furthermore, if the grayscale value is 0, the DMD is 0% ON. These experimental results indicate that the full projection cycle is required in order to properly generate 8-bit sinusoidal patterns. However, if only 0 or 255 grayscale values are necessary, a partial projection cycle is sufficient.



(a) (b) (c) (d)

Figure 1: Example of the projected timing signal with different grayscale values. (a) Green = 255 (Red = Blue = 0); (b) Green = 128 (Red = Blue = 0); (c) Green = 64 (Red = Blue = 0); (c) Green = 0 (Red = Blue = 0).

2.2 Three-step phase-shifting algorithm

Phase-shifting algorithms have been extensively employed in optical metrology due to their speed, accuracy, and robustness to noise. Even though there are numerous phase-shifting algorithms that have been developed, a simple three-step phase-shifting algorithm is usually preferable for high-speed 3D shape measurement since this is the minimum number of patterns required to solve for the phase value pixel by pixel, albeit the random noise effect may be significant. A three-step phase-shifting algorithm with a phase shift of $2\pi/3$ can be realized by capturing three fringe images with equal phase shifts, and these three images can be mathematically described as

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi - 2\pi/3], \tag{1}$$
$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi], \tag{2}$$
$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi + 2\pi/3]. \tag{3}$$

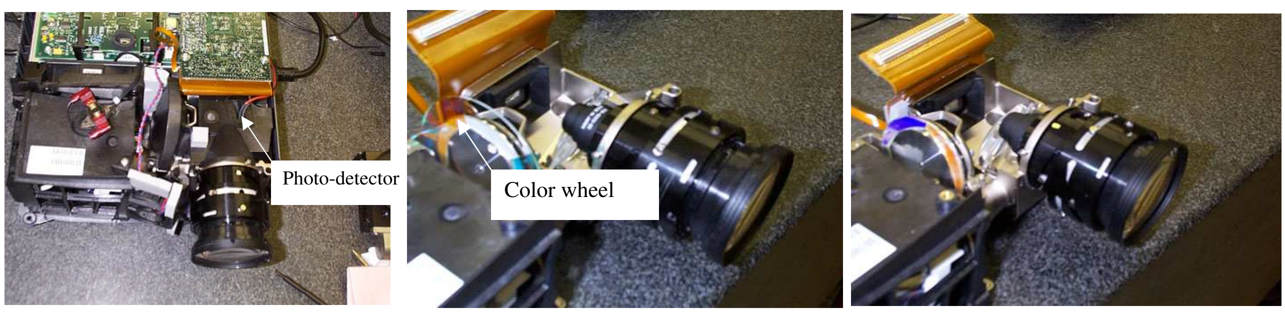
Where $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, and $\phi(x,y)$ the phase to be solved for. The phase can be calculated by simultaneously solving these three equations,

$$\phi(x,y) = \tan^{-1}\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}. \tag{4}$$

Due to the nature of the arctangent function, the phase is wrapped with a range from $-\pi$ to π with a modulus of 2π. In order to obtain a continuous phase map, a spatial or temporal phase unwrapping algorithm is required. This phase unwrapping essentially detects and removes 2π discontinuities by adding or subtracting integer multiples of 2π .[15] Once the system is calibrated, (x,y,z) coordinates can be reconstructed from the phase.[16]

3. REAL-TIME 3D SHAPE MEASUREMENT WITH A MODIFIED DLP PROJECTOR

Our efforts toward superfast 3D shape measurement started with modifying a DLP projector mainly because of the availability of hardware at the time and the limitations of the other hardware components. The commercially available DLP projectors typically generate color images that are fed to the projectors. The colors are generated by putting a rapidly spinning color wheel into the optical path and properly synchronizing the color wheel with the computer-generated signal. The synchronization signal is usually picked up by a photo-sensor behind the color wheel with some associated electronics. Figure 2 shows photos of the projector we modified (Kodak DP900). The photo sensor behind the color wheel is shown in Fig. 2(a); this is used to detect the color filters and therefore used for synchronization purpose. Figures 2(b) and 2(c) respectively show the color wheel with and without color filters.



(a) (b) (c)

Figure 2: Color wheel and photosensor of the digital video projector. (a) The photo-sensor behind the color wheel; (b) Color wheel of the projector; (c) Color wheel after removing color filters. (Original figure was published in Ref.[17])

As discussed in subsection 2.1, DLP works off the time modulation to generate grayscale images, and thus synchronizing the projector and the camera becomes extremely important to properly capture the desired fringe images used for high-quality 3D shape measurement. Moreover, using color fringe patterns is not desirable for high-quality 3D shape measurement, so the elimination of color is vital. Furthermore, the commercially available DLP projectors are typically nonlinear devices (also called nonlinear gamma effect) to accommodate for human vision, but generating ideal sinusoidal patterns is required for high-quality 3D shape measurement. Meanwhile, the unique projection mechanism of DLP technology, sequentially projecting red, green, and blue channels, permits the natural way of high-speed 3D shape measurement if a three-step phase-shifting algorithm is used. In summary, to achieve high-speed 3D shape measurement at a desired high-quality with a commercially available DLP projector, the following hardware challenges need to be conquered: 1) elimination of the color wheel from the optical path; 2) precise synchronization between the camera and the projector; 3) corrections for the nonlinear gamma effects.

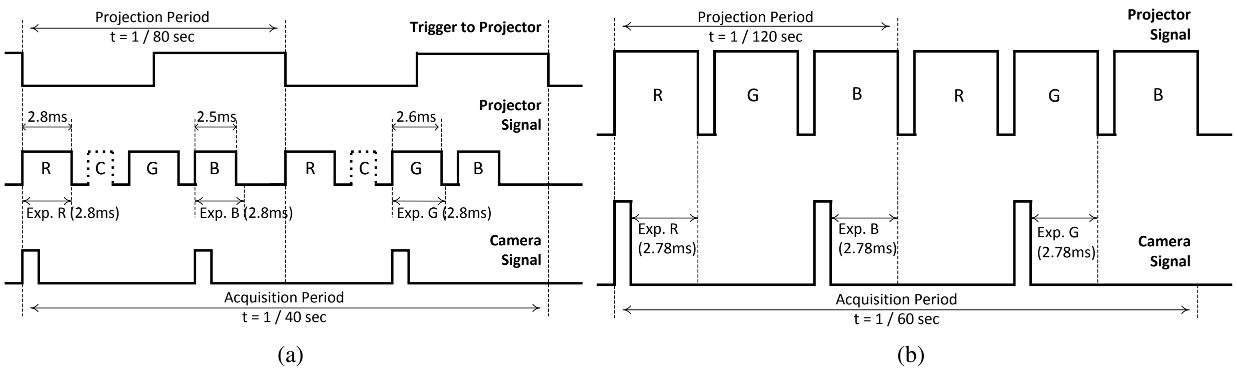


Figure 3: Timing chart of the measurement system. (a) The first projector (Kodak DP900) was modified without firmware changes; (b) The second projector (PLUS U5-632h) was modified with an additional PLUS Vision firmware update.

3.1 Real-time 3D shape acquisition

To conquer those aforementioned three challenges, modifying the commercially available digital video projector is required. The most important modifications we made were removing the color filters of the color wheel and supplying an external trigger signal such that the projector can still take the regular color image from the computer and project the red, green, and blue channels sequentially, albeit in monochromic mode. The external trigger signal was generated with micro-controller to mimic the signal from the photodetector such that the projector cannot tell whether the signal was from the photodetector or our circuit and thus behaves independently of the signal source.

After these modifications, the projector projects a monochrome fringe image for each of the RGB channels sequentially. Each "frame" of the projected image is actually three separate images. By removing the color wheel and placing each fringe image in a separate channel, the projector can produce three fringe images at 80 Hz (240 individual color channel refresh rate). Therefore, if three fringe images are sufficient to recover one 3D shape, the 3D measurement speed is up to 80 Hz. However, due to the speed limit of the camera used and the asynchronous data transfer time requirement, it takes two projection cycles to capture three fringe images; thus, the measurement speed is 40 Hz.[9] Figure 3(a) shows the timing chart for the real-time 3D shape measurement system.

It is important to note that, as indicated in Fig. 3(a) the timing of different color channels is different (red channel lasts the longest time, and blue channel lasts the shortest time) for the digital video projector we modified, making the precise synchronization between the projector and the camera more difficult because rapidly changing the camera exposure time from one frame to the next was not permitted. The synchronization between the projector and the camera requires a timing consuming trial-and-error process. It is also important to note that the projector also has a clear channel that is intended to increase the overall brightness of the projector, but this does not provide additional useful information for our 3D shape measurement purpose.

As addressed in subsection 2.2, three fringe images can be used to reconstruct one 3D shape if a three-step phase-shifting algorithm is used. This perfectly fits into the DLP technology schema where three patterns can be encoded into each of the three primary color channels of the projector. Since color fringe patterns are not desirable for 3D shape measurement, we developed a real-time 3D shape measurement system based on a single-chip DLP projector and white light technique.[9] Fig. 4 shows the system layout. The computer generated color encoded fringe image is sent to a single-chip DLP projector that projects three color channels sequentially and repeatedly in grayscale onto the object. The camera, precisely synchronized with projector, is used to capture three individual channels separately and quickly. By applying the three-step phase-shifting algorithm to three fringe images, the 3D geometry can be recovered. Averaging three fringe images will result in a texture image that can be further mapped onto the recovered 3D shape to enhance certain visual effects.

3.2 Projector nonlinear gamma correction

Since 3D geometry is directly recovered from the phase, the phase quality is essential to the measurement accuracy: any noise or distortion on the phase will be propagated to the final 3D measurement. Unlike a structured light system using a binary coding method, the digital fringe projection system requires calibrating for the nonlinearity of the projection and

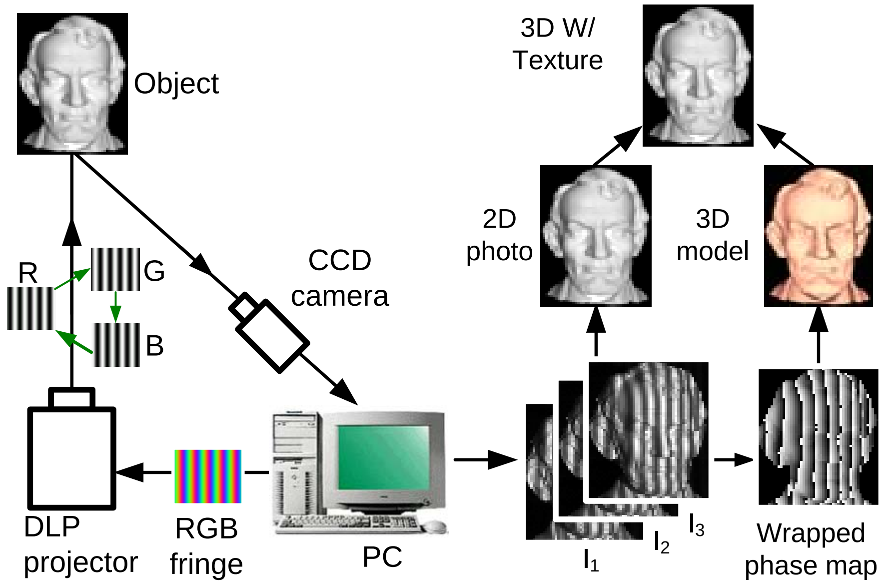


Figure 4: Real-time 3D shape measurement system layout. (Original figure was published in Ref.[5])

compensating for the errors associated with it. Even though nonlinearity correction is relatively mature with many methods developed,[18–23] our research found that the nonlinearity of the projector actually changes over time; this complicates the problem since a regular nonlinearity calibration is usually sufficient.[5] Nevertheless, good quality phase can be obtained after applying a proper nonlinear gamma correction algorithm.

3.3 Real-time 3D data processing and visualization

As aforementioned, real-time 3D shape measurement requires real-time 3D shape acquisition, reconstruction, and redisplay. The processing time is tremendous for computing the wrapped phase point by point using a standard arctangent function, and when phase unwrapping is factored in as well, the challenge becomes even more difficult. These are just some of the reasons why real-time 3D shape reconstruction was difficult about ten years ago (around the year 2004). By developing a new method for computing wrapped phase,[24] and substantially optimizing our phase unwrapping algorithm, we successfully achieved real-time 3D data processing for an image resolution of 532×500.[25] Figure 5 shows an example frame which is measuring human facial expressions in real time (40 Hz in this case).

There are, however, two issues associated with the first real-time 3D shape measurement system we developed:[25]

1. *Inaccurate calibration method.* To achieve real-time 3D data processing, the simple reference-plane-based calibration method was adopted. As a result, the recovered 3D geometry could be significantly distorted if the object is away from the reference plane, or if the hardware system is not properly configured.[16]

2. *Low phase quality.* The phase quality is reasonable but not the best in principle. This is because the three color channels have different illumination times, shown in Fig. 3(a), but the camera uses the exposure time to capture these channels. The result is not all channels are properly captured.

Further hardware modifications are required in order to solve for these two problems. Fortunately, PLUS Vision agreed to do firmware modifications for one of their projector models, PLUS U5-632h. With the company's assistance, besides removing color filters, the modified projector only projects red, green and blue channels without the clear channel, and all these channels have the same duration time. These modifications were highly desirable for high quality 3D shape measurement. Furthermore, because of these modifications, the projection speed can be at 120 Hz (or 360 Hz individual channel refreshing rate), speeding up the whole measurement (to 120 Hz). Figure 3(b) shows the timing chart for the second generation real-time 3D shape measurement system we developed.[26]

Figure 5: Simultaneous 3D data acquisition, reconstruction, and display at 30 fps. (Original figure was published in Ref.[5])

Besides improved phase quality, the new system also adopted the more complex, yet more accurate, calibration method we developed.[16] The new calibration method requires substantial computation power in order to achieve real-time 3D data processing, making it almost impossible to achieve on a central processing unit (CPU). Fortunately, graphics processing unit (GPU) technologies were invented and quickly adopted.

By taking advantage of the processing power of the GPU, 3D coordinate calculations can be performed in real time with an ordinary personal computer with an NVidia graphics card.[27] Moreover, because 3D shape data is already on the graphics card, it can be rendered immediately without any delay. Therefore, by these means, real-time 3D geometry visualization can also be realized in real time simultaneously. Also, because only the phase data, instead of the 3D coordinates and the surface normals, are transmitted to graphics card for visualization, this technique reduces the data transmission load on the graphics card significantly (approximately six times smaller). In short, by utilizing the processing power of GPU for 3D coordinate calculations, real-time 3D geometry reconstruction and visualization can be performed rapidly and in real time.

Figure 5 shows an experimental result of measuring a live human face. The right figure shows the real subject, and the left shows the 3D geometry acquired and rendered on the computer screen at the same time. The simultaneous 3D data acquisition, reconstruction, and display speed achieved is 30 frames/second with more than 300,000 points per frame being acquired.

These technologies, though successful, require substantial projector modifications, and sometimes these modifications are impossible without the projector manufacturer's involvement. Fortunately, with about a decade of effort on high-speed 3D shape measurement, projector manufacturers are beginning to realize the opportunities in this field by producing affordable specialized projectors: LogicPD LightCommander being the first, and Texas Instruments (TI) following up with their LightCrafter series.

4. SUPERFAST 3D SHAPE MEASUREMENT WITH BINARY DEFOCUSING TECHNIQUES

As 3D shape measurement technologies become more accurate and become faster, such as with the real-time systems which have been proposed, the number of potential applications in the field continue to grow. These technologies have already been applied successfully to the medical field, the entertainment field, the manufacturing field, and many more. Up until now, the definition for a real-time system might be one that can capture at a rate of 30 or higher Hz. This speed enables a system to capture scenes or objects that are not too rapidly changing or moving around. A good example of this might be one's facial expression. If an object being captured does move at a very fast pace, however,such as a speaking mouth or a live, beating heart, some interesting challenges need to be overcome to realize a kHz scanning rate. Fortunately, there have been advances in hardware platforms (e.g., DLP Discovery, DLP LightCommander, and the DLP LightCrafter); these advancements to the hardware allow for them to display 8-bit grayscale images at a few hundred Hz and allow for the display of binary images at an even faster kilo-Hertz or higher rate. These advancements have driven us to invent the binary defocusing technique[10] such that a scanning at a kHz rate can be achieved with good quality.

Zhang et al.[11] have capitalized on the advancements made in the hardware platforms and successfully achieved a 3D shape measurement speed of tens of kHz. Albeit fast, this new system comes with its own challenges and setbacks: (a) the presence of high-frequency harmonics impact the measurement accuracy; (b) the generated binary pattern has an optimal quality at a certain range, and the region for this range is relatively small thus the result may be a less accurate depth measurement;[28] (c) conventional calibration methods take into account that the projector is in focus yet this new capture method relies upon the projector being defocused; the result is needing a more complex calibration technique;[29] and (d) high-quality fringe patterns at different spatial frequencies are hard to generate simultaneously.[30] To overcome some of these challenges, the 3D shape measurement field has borrowed pulse width modulation (PWM) techniques from the Power Electronics field with Ayubi et al.[31] inventing the sinusoidal pulse width modulation (SPWM) technique and Wang and Zhang[12] inventing the optimal pulse width modulation (OPWM) technique. These techniques each work to improve the phase quality, yet they too still face their own issues: especially if the stripes in the fringe images are either too narrow or too wide.[32]

Given the discrete nature of these fringe patterns, however, there might not be many improvements that can be made in this regard. It should be stated that these pulse width modulation developments are all one dimensional. It would be logical then that certain limitations can be lifted if improvements can be made in two dimensions instead. This is the driving hypothesis behind Lohry and Zhang's[33] new technique to locally modulate the pixels as to emulate a triangular pattern. This is done in aims to reduce the influence of high-frequency harmonics.

Other research has been done to improve measurement quality by adopting dithering techniques. Dithering techniques, also sometimes called half-toning, have been around since the 1960s;[34] they can be used to represent grayscale images with binary images and given the fast speeds at which modern projectors can display binary images, this becomes important. In regard to dithering application in the 3D shape measurement field,[35] Wang and Zhang's work[13] extended the simple Bayer-dithering technique and eventually the error-diffusion techniques.[36–40] It should be noted that these techniques improve the quality of measurement when the fringe stripes are wide; improvement is not as noticeable when the fringe stripes are narrow. It should also be described that the majority of these dithering techniques involve applying some sort of matrix or kernel to the generated grayscale images to result in a binary image. The resulting image however may not be optimal as these "binarization" techniques may not take into account some of the inherent structures in the grayscale images which are being used (such as sinusoidal structures in fringe images). Optimizations can be had, then, if these unique sinusoidal structures within the fringe patterns are assumed and capitalized upon. Recently, we have developed several algorithms[41–44] to noticeably improve the aforementioned approaches to dithering.

One example of our improvements can be seen in Figure 6. A 3D sculpture was measured with a fringe period of $T = 90$ pixels and with the projector being slightly defocused. The first row of the results display the captured structured images; the second row displays the rendered 3D results. The results show that when the projector is nearly in focus, the binary structure is clear for the squared binary patterns and that the optimized dithered patterns are sinusoidal in nature. It should also be noted that neither the squared binary method nor the pulse width modulation method generate high-quality 3D results whereas the dithering and optimized-dithering techniques perform well in the sculpture's reconstruction. The last result which should be derived from this experiment is that the optimized-dithering technique is visibly better than the regular dithering method.

A second example of our work in realizing a system which can perform kHz 3D shape measurement can be seen in Figure 7. This system captures live rabbit hearts as they beat at a rate of approximately 200 beats per minute.[35] This specific system is composed of the Texas Instruments DLP LightCrafter projector and a Vision Research Phantom V9.1 high-speed CMOS camera. As in our aforementioned systems, the camera was triggered to capture by an external electronic circuit that senses the timing signal from the projector and synchronizes the system. The camera's resolution was 576×576 and the projector's resolution was 608×648. The projector's rate at which it switched binary patterns to be displayed was 2000 Hz, and thus the camera was set to capture at 2000 Hz, as well. A two wavelength phase-shifting technique was used with the shorter wavelength being the OPWN pattern[12] and longer wavelength being Stucki-dithered patterns.[40] The resulting images show the clear and dynamic motion of the rabbit heart as it was well captured. It was found that a speed

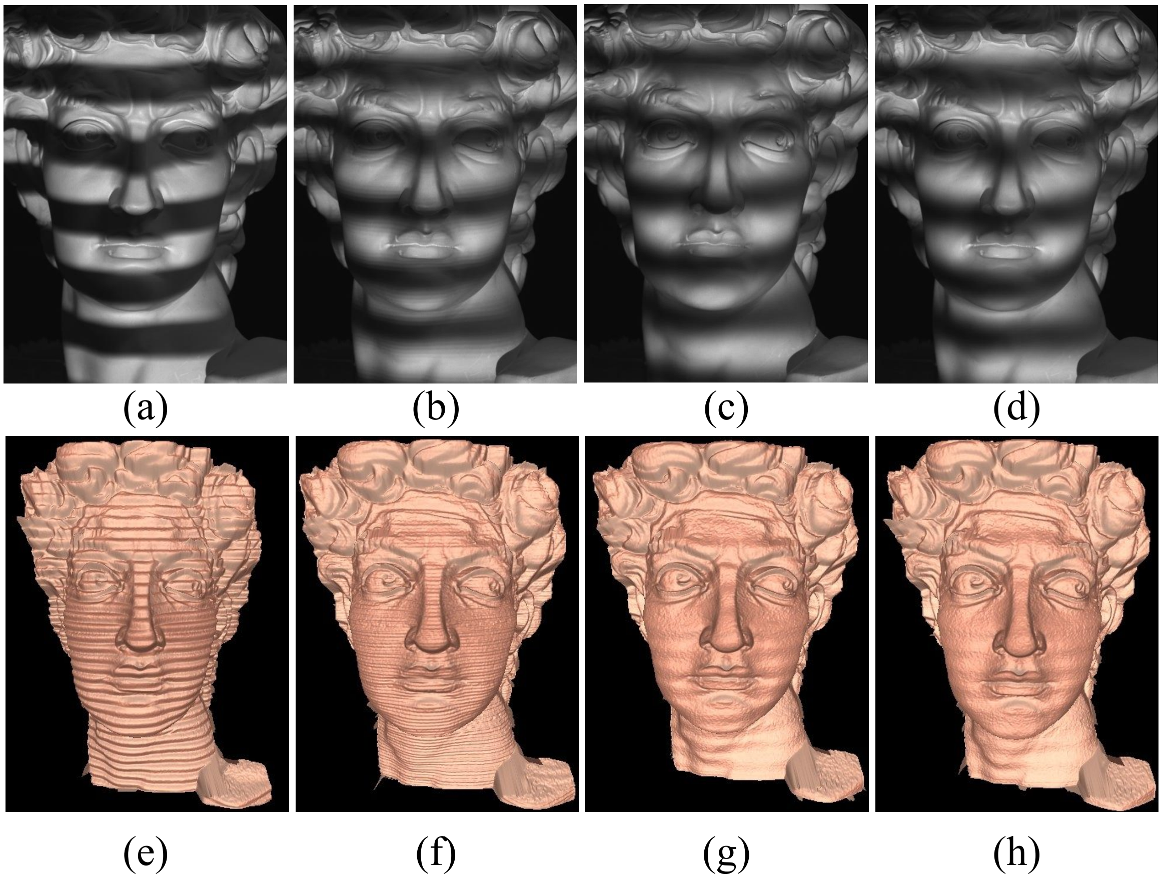


Figure 6: Captured patterns with the fringe period T = 90 pixels when the projector is slightly defocused. (a) Squared binary pattern; (b) PWM pattern; (c) dithering pattern; (d) optimized-dithering pattern; (e)-(h) corresponding reconstructed 3D results of (a)-(d). (Original figure was published in Ref.[45])

of at least 800 Hz was required to capture the heart accurately without being distorted by motion, and thus without the employment of the above mentioned binary defocusing techniques this would not have been possible.

5. CONCLUSIONS

This paper has summarized the route we took to achieve real-time to kHz 3D shape measurement speeds by leveraging the DLP technologies that were invented by TI. These technologies have already seen extensive applications, and there are many more applications in which these technologies can be applied. The fundamental barriers of achieving superfast 3D shape measurement were successfully overcome through different innovations, but there are still a number of challenges including the use of near infrared (NIR) light, accuracy improvements, the reliability of the DLP systems in industrial environments, and the sustainability of such a technology in harsh, and sometimes outdoor, applications. We believe further innovations are required to allow real-time to superfast 3D shape measurement technologies to be adopted on a much larger scale.

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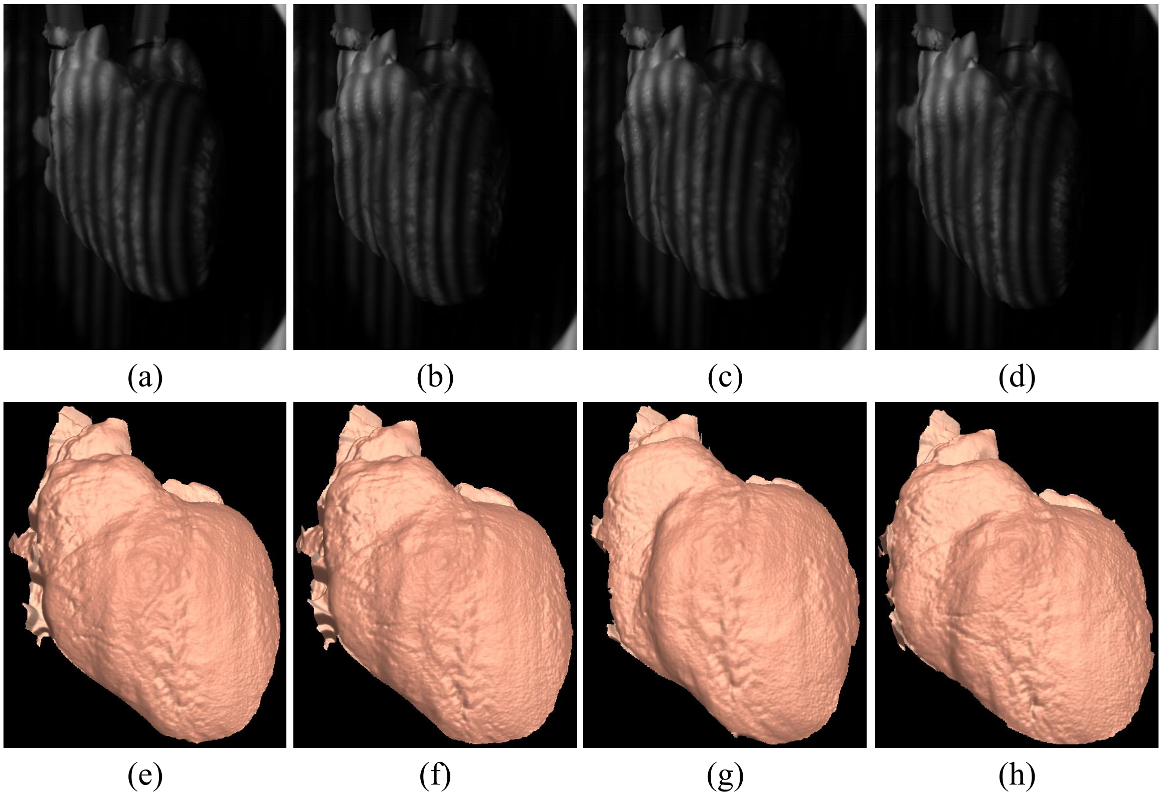

Figure 7: Example of capturing live rabbit hearts with binary defocusing techniques. (a)-(d) Captured fringes of a live rabbit heart; (e)-(h) Corresponding reconstructed 3D results of (a)-(d). (Original figure was published in Ref.[45])

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